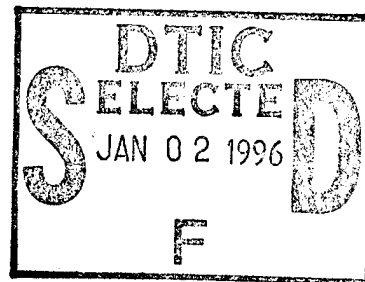NBSIR 82-2556

An Analysis of Smoldering Fires in Closed Compartments and Their Hazard Due to Carbon Monoxide

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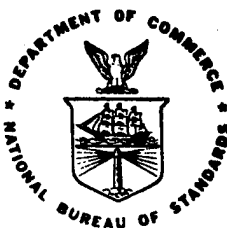# AN ANALYSIS OF SMOLDERING FIRES IN CLOSED COMPARTMENTS AND THEIR HAZARD DUE TO CARBON MONOXIDE

J. Quintiere, M. Birky, F. McDonald and G. Smith

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An Analysis of Smoldering Fires in Closed Compartments
and Their Hazard Due to Carbon Monoxide

by

J.G. Quintiere, M. Birky, F. Macdonald, G. Smith

Abstract

A review was made of smoldering fire experiments conducted in closed rooms and buildings. The results were summarized by tabulating maximum levels of CO, the time integral of CO concentration ("dose"), CO_2, temperature rise and oxygen consumption. A hazard time based on the attainment of a CO dose equal to 4.5% CO-minutes and the time for transition to flaming were also tabulated. The likelihood of reaching a critical CO condition during smoldering seems to be comparable to the likelihood of having transition to flaming occur. A theoretical model, requiring inputs of CO production rate and energy release rate, was executed and compared with available data. The theoretical results for CO concentration as a function of time were in good agreement with the experimental data. The model offers a means of extrapolating test data to compartments of various size in order to assess the general hazard of CO due to smoldering.

Key Words: Carbon monoxide, closed space, review, smoldering fires.

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Introduction

The hazard of smoldering fires has been well documented by fire statistics. Twenty-seven percent of the deaths due to fire in the United States have been attributed to residential fires involving mattresses or upholstered furniture initiated by smoking materials [1]. This fire scenario commences with a smoldering fire propagation which may go through a transition to flaming fire spread. The fire victims could be in the same room as the fire or in another room of the dwelling. It is not clear from fire incidence data whether victims succumb during the smoldering phase or during the possible subsequent flaming phase.

Although this fire scenario is more than five times as common as any other [1], its characteristics and behavior have been studied very little. There are only a few experimental studies for a variety of materials and furnishings to document the general behavior of smoldering propagation and its transition to flaming. Consequently the mechanisms for smoldering decomposition and its transition to flaming are not well understood. For example, no models have been developed to predict the rate of CO evolved or the time for flaming to occur. Also the dynamics of the flow of combustion products, which originates at the smoldering source and spreads to the boundaries of the dwelling space, have not been delineated. A better understanding of these phenomena could more completely define the parameters which control the hazard of the "smoldering" fire scenario.

The research that has been done divides into very basic and very applied studies. The fundamental research has dealt with simple geometric configurations and has led to some insight into the mechanism of smoldering and the prediction of its propagation [2-8].

The applied research has [9-15] considered the smoldering of
furnishing materials in full-scale experiments involving a single room,
several rooms, or even an entire house. Usually, the criterion for
conducting these experiments was realism, e.g., ignition by a cigarette,
inclusion of blankets, sheets, etc. Typically the temperature and composition
of the accumulated products of combustion were recorded. The mechanism of
smoldering was not addressed in these full-scale experiments, and in nearly
all cases, the rate of mass loss during smoldering was not measured or reported.

The motivation for this investigation was to try to establish a quanti-
tative result of the hazard during the smoldering period of a fire. The
objectives were two-fold: (1) to consolidate for analysis the data
of available full-scale smoldering experiments, and (2) to develop a model
for the prediction of CO concentration in an enclosure subject to smoldering.

Compartment Smoldering Experiments

A review of the literature was made in order to assemble temperature
and concentration data from smoldering fire experiments in compartments. Only
those experiments in which measurements were made in a closed space were
considered. The "closed space" could have been a single room with a closed
door, or an entire house with all external doors and windows closed (or, perhaps,
open a small amount). The literature review includes experiments in a single
family house by Bukowski, Christian, and Waterman [9], tests of various
mattress and upholstered chair materials by Hafer and Yuill [10], room tests

by Sumi and Williams-Lear [11], experiments in a mobile home by Bukowski [12], and experiments in an apartment by Heskestad [13] and Kung [14]. Recent experiments conducted at the National Bureau of Standards (NBS) [15] were also evaluated.

These recent NBS experiments [15] were to serve as a guide for the developmental of a mathematical model and a basis for its verification. They were conducted in a closed room 2.44 m high and 8.83 m^2 in floor area. The only opening was a horizontal slit at the floor with dimensions 76 cm by 2.5 cm high. The smoldered material was either a loosely packed bed of cotton 10 to 15 cm thick or two adjacent blocks of flexible polyurethane foam designated as GM-21* 15 cm thick. Smoldering was initiated by an electric heater centrally located within the material. Also a chair of the same type used by Bukowski [12] was smoldered. In each of these experiments the mass loss was measured along with temperature and specie concentrations at various positions in the room. The gas measurements were made between the smoldering material and one wall at heights of 30.5, 76.2, 168, and 236 cm above the floor. The smoldering material was placed on a load cell platform which was approximately 33 cm above the floor, and the ignition point on the chair was approximately 43 cm above its base.

The experimental data reviewed in the literature and obtained in the NBS study [15] are listed in Tables Ia and Ib. Table Ia lists the materials burned, and the type of enclosure including its volume and ventilation conditions. Table Ib lists the corresponding experimental critical results during smoldering: maximum carbon monoxide concentration, minimum oxygen concentration, maximum carbon dioxide concentration, maximum temperature rise, and the time of transition to flaming.

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*GM is a material from the material bank of the Product Research Committee, described in Fire Research on Cellular Plastics: The Final Report of the Products Research Committee, Lib. Cong. No. 80-83306, (1980).

Selecting a Hazard Criterion

It is useful to analyze these data in order to establish some basis
for deciding whether the smoldering fire conditions pose a threat to human
safety. The degree of impairment which constitutes a threat is somewhat
subjective. Also many factors bear on the process so that a unique hazard
criterion is not possible to define. Although CO appears to be the principle
hazardous agent of smoldering fires, other combustion products generated can
increase the hazard. They can affect the respiratory rate, in addition to
the normal rate corresponding to the activity of the person. Thus, the
inhaled rate of combustion products will vary, and a specified exposure
to CO is not sufficient to define a unique physiological effect. Despite these
factors, a reasonably distinct condition will be sought so that a hazard
criterion can be expressed solely as a function of the exposure CO concen-
tration. This will provide at least a reference point for discussion.

The basis for determining the hazard caused by exposure to CO is the
concentration of carboxyhemoglobin (COHb) which forms in the blood. This
displaces the oxyhemoglobin, therefore starving the body of oxygen. The degree
to which this occurs has been correlated with the response of healthy adults [16].
The COHB level is usually measured in per cent saturation in the blood with
100% corresponding to the condition in which all of the hemoglobin has
combined with CO to form COHb. For example, 20-40% COHb corresponds to
throbbing or severe headache and nausea, and greater than 50% COHb leads
to coma or death, if untreated [16]. A general formula that describes the
relationship between the exposed CO concentration (x in % volume) and the
conversion to COHb in the blood (z in % saturation in blood) was developed
by Coburn, Foster and Kane [17]. The formula basically is a conservation
equation which states that the rate of COHb (dz/dt) formed is equal to the

sum of the inhaled or exogenous component plus the body generated or endogenous component. In considering extreme effects associated with combustion products, the endogenous effect is relatively small. Since the exogenous effect results from the CO partial pressure difference between the exposure gases and the pulmonary capillaries, it can be a positive or a negative value. COHb will increase when exposed to a fixed CO concentration, reaching an equilibrium value in generally several hours. On subsequent exposure to normal air, COHb will decay to its normal level in the same manner. Further details of the process can be found in the literature [16,17]. The following equation can be developed by using the values for fixed parameters as suggested by Stewart [16] and Zullo [18].

$$\frac{dz}{dt} = \left(0.69 \ x - \frac{0.042z}{(100-z)} \right) k_v + 6.4 \times 10^{-4} \tag{1}$$

where z is % COHb saturation,

$\quad$ x is % volume of CO in the exposure gas,

$\quad$ k_v is a ventilation parameter in mℓ/min-mm Hg,

and $\quad$ t is time in minutes.

The value of k_v depends on the ventilation rate and therefore the activity level of the person. Zullo [18] provides data such that the following values for k_v can be determined for three activity levels:

$$k_v = \begin{cases} 6.6 \ \text{m}\ell/\text{mm Hg, resting} \\ 15.4 \ \text{m}\ell/\text{min-mm Hg, moderate work} \\ 24.7 \ \text{m}\ell/\text{min-mm Hg, heavy work} \end{cases}$$

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A criterion for hazard will be derived from Eq. (1) by making some approximations. In principle, the activity level, age and health of the person along with the expsoure concentration of CO will be sufficient to compute the COHb level as a function of time. A hazard time can then be found by deciding on a specific unacceptable COHb level. The variations and uncertainties in these quantities justify approximations in the analysis in order to arrive at a general criterion. Of course, this result to follow will only provide a general global reference, and will not be accurate in specific cases. The approximations are described below:

(1) The threshold for discomfort in healthy adults and a possible lethal condition for persons with heart disease may be taken as z = 20%. Hence, by considering $0 \leq z \leq 20$ as the range of interest, Eq. (1) will be linearized by approximating the term z/(100-z) as z/100.

(2) The anticipated range of CO conditions relative to smoldering fires is 0.01 to 1% (or 100 to 10,000 ppm). Also since the potential victim is believed to be asleep in many smoldering fire scenarios, a k_v corresponding to the rest state will be used. Hence, the endogenous term (6.4×10^{-4} % COHb/min) will be negligible compared to the exogenous term. On similar reasoning, the initial concentration of COHb will be taken as zero.

Thus, Eq. (1) is approximated as follows:

$$\frac{dz}{dt} = 6.6 \ (0.69 \ x \ (t) - 0.042 \ z) \tag{2}$$

with z = 0 at t = 0.

A general solution is given as

$$z = 4.6 \, e^{-2.8 \times 10^{-3} t} \int_0^t e^{2.8 \times 10^{-3} \tau} \, x(\tau) \, d\tau \qquad (3)$$

To justify a final approximation, a representative upper time limit of interest in smoldering fires will be taken as 2.5 hours (150 min.). Also a power law description will be considered for CO concentration since this is a good representation for smoldering in closed compartments. That is,

$$x(t) = at^n. \qquad (4)$$

This is substituted into Eq. (3) along with approximations for the exponentials since $2.8 \times 10^{-3} t$ is small for $t \leq 150$ minutes. The result can be written as

$$z = 0.69 \, k_v \int_0^t x(\tau) \, d\tau \left[1 - \frac{bt}{n+z} - \frac{n+1}{n+z} (bt)^2 \right] \qquad (5)$$

where $b = 4.2 \times 10^{-4} \, k_v \, \text{min}^{-1}$,

$k_v = 6.6 \, \text{m}\ell/\text{min-mmHg}$,

and $x = at^n$

For smoldering rates to be discussed, it may be reasonable to expect n between 1 and 3. Such arguments lead to the conclusion that the bracket term in Eq. (5) can be as low as 0.75 approximately. Considering this effect small in terms of the precision attributable to an overall hazard criterion, the following criterion is derived.

$$D(t) \equiv \int_0^t x(\tau) \, d\tau = \frac{20}{(0.69)(6.6)} \sim 4.5 \, \% \, CO - \text{min} \qquad (6)$$

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The variable D defined here will be referred to as the CO-dose, and 4.5%-min represents its critical value relative to hazard. This dose variable can be easily computed from experimental data or from predicted CO concentrations over time, and the time at which it attains 4.5%-min defines the degree of hazard. Table Ib lists the maximum value of D achieved in each experiment, and the time at which the critical dose is reached.

Unquestionably the criterion for hazard due to CO exposure is somewhat arbitrary as expressed by Eq. (6). It has been based on some approximations to the Coburn et al. equation [17], holds for times less than about 150 minutes, has selected 20% COHb as an "incapacitation" point, and has assumed a human activity in the resting state. For other conditions, the critical value in Eq. (6) will change. An increase in the activity level will decrease the critical value for dose, and the dose integral will overestimate the physiological effect for times longer than those for which the mathematical approximations are valid.

Based on this CO hazard criterion and on similar considerations for the other possible sources of hazard, the general results of Table 1 may be summarized as follows: The effects of elevated temperature, low oxygen, and high carbon dioxide levels were not a significant threat to life safety in these limited experiments; however, the level of carbon monoxide in smoldering can reach a hazardous level. The onset of flaming, after which hazardous conditions will very likely result, is a variable event, and the factors which promote its occurrence are not obvious. Distributions of the times to flaming and the times to reach the critical (4.5%-min) CO dose are shown in figure 1. Of the forty experiments, 24 resulted in transition to flaming and 17 reached a critical CO dose during

smoldering. Of these 17, 10 never developed to the flaming state while the other 7 did. It appears that hazardous conditions due to CO occur in 50 to 150 minutes and that the transition to flaming is also very likely in this period. Hence the hazard of smoldering initiated combustion is either the incapacitation of a person due to the inhalation of CO, or the transition to flaming combustion which would increase both the CO and temperature levels of the combustion products. Both of hazards appear to have a similar chance to occur in a period of 1 to 2-1/2 hours. Which will occur first can not be answered, since the transition to flaming can not be predicted.

Theoretical Analysis

The model applied to predict the CO concentration in the enclosure is based on the analysis developed by Zukoski [19] to predict the time required for a "closed" room to fill with products of combustion from a small fire. The smoldering phenomenon is treated as a point source of energy and CO which gives rise to a weakly buoyant plume, and the room is assumed to leak at the floor. All closed building compartments tend to leak and a floor leak corresponds to the usual space under a closed door. The plume causes a hot descending layer in the room and the CO concentration is taken to be uniform in this layer. A schematic of this process is shown in figure 2.

A tracing sketch taken from a photograph of the actual process is shown in figure 3. The faintness of the smoke in the plume and hot layer precluded a distinct photograph for illustration. The sharpness of a hot layer interface is not always clear, and this concept is less valid as the descending layer gets close to the floor. Nevertheless, a point source plume is probably a good model of the smoldering plume but the homogeneous layer assumption may need more support.

The governing equation for the layer height given by Zukoski [19] in dimensionless variables is

$$\frac{dy}{d\tau} + Q* + \alpha(Q*)^{1/3}y^{5/3} = 0 \qquad (7a)$$

for $0 \leq y < 1$ with $y = 1$ at $\tau = 0$ and

$$\frac{dy}{d\tau} + Q* = 0 \qquad (7b)$$

for $-\frac{L}{H_c} \leq y \leq 0$. Once the layer reaches the floor, $y = -L/H_c$ for all time thereafter. These equations arise from a mass balance on the lower cold volume of gas in the compartment. The second term in Eq. (7a) represents the leak rate which is proportional to the energy release rate ($\dot{Q}$) of the smoldering source minus the rate of heat loss from the hot layer which are assumed negligible here. This term is generally small compared to the third term for smoldering fire sources while the layer height (H) is above the position of the source (L). The third term represents the rate of mass entrained by the plume.

The dimensionless quantities are given as follows:

dimensionless time, $\tau = t\sqrt{g/H_c} \ (H_c^2/S)$;

dimensionless heat, $Q* = \dot{Q}/(\rho_o T_o c_p \sqrt{gH_c} \ H_c^2)$;

dimensionless layer position, $y = H/H_c$;

and entrainment parameter, $\alpha = 1/5.4$.

The floor area is designated by S, and the other geometric variables are displayed in figure 2.

The rate of energy release of the point source plume is given by

$$\dot{Q} = \dot{m} \, \Delta H \tag{8}$$

where $\dot{m}$ is the rate of mass loss due to smoldering and ΔH is the heat of reaction for the smoldering process. Here, the assumption is made that all of the energy release due to smoldering is convected away by the plume. Plume radiation and conduction heat losses in the smoldering material are neglected. It will be shown that significant uncertainties in the value of ΔH exist which overshadow the effect of ignoring these heat losses. Fortunately these uncertainties seem to have a small impact on the predicted results.

The conservation equation for CO was developed from a control volume enclosing the hot layer and the plume. The plume was assumed to have negligible volume, and the density of hot layer was taken as that of the air in the lower layer. This is consistent with the Boussinesq model for the plume [19] and is justified by the low temperature rise in smoldering fires as observed from Table I. By employing the conservation of mass as well, the equation for CO mass concentration, Y, with or without leakage from the hot layer, follows:

$$\frac{dY}{d\tau} = \frac{\gamma c_p T_o}{\Delta H} \cdot \frac{Q^*}{(1-y)} - \alpha Q^{1/3} y^{5/3} Y/(1-y) \text{ for } 0 \le y \le 1 \tag{9a}$$

$$\frac{dY}{d\tau} = \left(\frac{\gamma c_p T_o}{\Delta H} \right) \left(\frac{Q^*}{1-y} \right) \text{ for } -\frac{L}{H_c} \le y \le 0 \tag{9b}$$

where γ is the effective stoichiometric mass ratio of CO produced to mass of material lost.

The dose parameter is computed as follows:

$$D = \int_{t_o}^{t} Y dt \qquad (10)$$

In the theoretical calculations the initial time t_o corresponds to the time
at which the layer interface reaches a specific height of interest. This
height could represent the position of a CO sensor or a likely position
that a person would be at. In analysis of the experimental data of
Table I, t_o is taken as zero.

A computer program was written to solve equations (7), (9) and (10) numeri-
cally. The apparent singularity in Eq. (9a) was avoided by small-time analytical
solutions as shown by Cooper [20]. The rate of mass loss as a function of
time was derived from available experimental data. Two other parameters,
γ and ΔH, must be specified for the smoldering material. These were also
derived from experimental data. This process will be described.

Comparison with Experimental Results

The two NBS tests [15], T18 polyurethane and T22 cotton, were examined first.
The mass loss rate was determined to be approximately linear in time up until
the fuel limit was reached, i.e.,

$$\dot{m} = ct \qquad (11)$$

with "c" respectively 0.206 gm/min^2 for the polyurethane and 0.33 g/min^2 for
the cotton. The heat source was taken at $L = 0.33m$ in these calculations.

Approximate values for ΔH were suggested by Ohlemiller [21] as 1.05 kJ/g for polyurethane and 2.1 kJ/g for cotton. Values for γ were then empirically determined using the upper most probe value for Y(CO) in Equation (9) at a sufficiently long time such that the hot layer position was at or near the floor. Thus, the value of y would be approximately equal to $(-L/H_c)$. The values found for γ were 0.085 for cotton and 0.11 for polyurethane.

An alternative method was also used to evaluate ΔH and γ for these materials. This made use of the analytical data taken from the NBS toxicity "protocol" apparatus [22]. This apparatus consists of a 194 ℓ closed chamber in which a small sample (several grams) of material is thermally decomposed in an electric furnace. The cotton and polyurethane materials examined in the closed room tests were decomposed (without flaming) in this apparatus. The gas temperature, CO and O_2 concentration measurements, along with the initial and final mass measurements of the samples, were used to estimate ΔH and γ. The respective maximum and minimum records for CO and O_2 were associated with the final sample mass at the end of the test. The parameters were then calculated from

$$\gamma = \frac{m_{CO}}{m_o - m_f} \qquad (12)$$

and

$$\Delta H = \frac{m_{O_2} \Delta H_{O_2}}{m_o - m_f} \qquad (13)$$

based on the assumption that the constancy of the heat of combustion per unit mass of oxygen (ΔH_{O_2}) holds for these decomposition reactions with a value of 13 kJ/g O_2 [23]. The other variables in Eqns. (12) and (13) are given as follows:

m_{co} — the maximum mass of CO produced

m_{O_2} — the maximum mass of O_2 consumed

m_o — the initial sample mass

and m_f — the final sample mass

The results of these calculations for a number of tests with different initial mass loadings yielded the values listed below:

Cotton: $\gamma = 0.11$ g/g, $\Delta H = 11 \pm 1$ kJ/g

Polyurethane: $\gamma = 0.10 \, {}^{+\,0.01}_{-\,0.04}$ g/g, $\Delta H = 15 \pm 8$ kJ/g

The variation in the values represents the differences among the test results for different sample loadings. The significance of these results is their general agreement with the "best fit" values for γ from the full-scale experiments, and their similarity for the two materials. But these derived ΔH values are an order of magnitude higher than the suggested values by Ohlemiller [21]. Fortunately this uncertainty in ΔH does not have a great impact on the computed results produced from the two sets of parameters, nor on their general agreement with the full-scale data. These comparisons are shown in Figure 4 for cotton and Figure 5 for polyurethane.

The results in Figures 4 and 5 show the long time scale typical of smoldering fires. The time at which each probe begins to record an increase in CO concentration is somewhat apparent from the data. These probe times could be interpreted as the time corresponding to the descending hot layer of CO. The clarity of this interpretation is not sufficient to test the predicted arrival times for the layer. However the general magnitude of the predicted results may be of interest and therefore are listed below for the polyurethane test:

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probe position, y	0.64	0.21	-0.01
arrival time for ΔH=15 kJ/g	150s	480s	1400s
arrival time for ΔH=1.05 kJ/g	270s	900s	3900s

Similar results are predicted for the cotton test. The order of magnitude of the predicted times seem to be in agreement with the times suggested by the data. The long arrival time for the probe near the source, calculated using the lower estimate for ΔH, may suggest that the higher value estimates of ΔH are more correct. More information is needed to resolve this issue.

The upholstered chair experiment [15] was analyzed next. Only the data for the sensor near the ceiling will be shown, since these should be representative of the idealized layer concentration. The predicted CO layer concentration was based on an experimental smoldering rate of

$$\dot{m} = \begin{cases} (0.10 \text{ g/min}^2)t + (0.0185 \text{ g/min}^3)t^2, & 0 < t < 73 \text{ min.} \\ (60 \text{ g/min}^2), & 73 \le t \le 120 \text{ min.} \end{cases} \tag{14}$$

and ΔH was selected as 1.5 kJ/g since the chair was composed of cotton and poly-urethane. The "best-fit" value for γ was found to be 0.11. Based on the previous discussion for the NBS polyurethane and cotton results, a higher value could also have been selected for ΔH. Since the uncertainty in ΔH appears to have a small effect on the predicted results, the smaller value was settled on. It is noted, however, that the "best-fit" value for γ is nearly the average of the previous values found for the pure cotton and polyurethane materials.

The predicted results are compared to the measured CO concentrations in Figure 6. The predicted height of the hot layer is also plotted as a function

of time. It initially falls at a relatively fast rate due to entrainment by the plume, then slows as it approaches the idealized heat source at 0.76 m above the floor. It then descends more rapidly as the smoldering rate increases, reaching the floor at 67 minutes. The test was allowed to proceed for nearly two hours. Flaming did not occur and the upholostery was almost entirely consumed.

Since the same chair had been used in the mobile home experiments by Bukowski, the mass loss rate given by Eq. (8) was used as a basis for predicting the CO concentrations in these experiments. A schematic of the mobile home is shown in Figure 7. The chair was burned in the living room, and CO measurements were made in the hall, 1.5 m above the floor, and in the rear bedroom, 0.9 m above the floor. Two experiments were compared: MH3 which had the bedroom doors open, and MH5 which had the doors closed. Doors and windows to the outside were closed and the forced air ventilation system was off. The previous values of ΔH and γ for the chair were used, but the source position was taken at $L = 43$ cm since the chair rested on the floor in this case. The predicted CO concentrations for the two experiments are compared with the measured results in Figure 7. The arrows on the predicted curves indicate the time at which the idealized hot layer interface reaches the hall sensor (H) for tests MH3 and MH5 and the bedroom sensor (RB) for MH3. As seen, the predicted results are in good qualitative agreement with the measurements but they are displaced to the left. Although an attempt was made to use the same ignition procedure for the chair, this displacement could be due to lack of reproducibility of the

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ignition and early smoldering propagation. The predicted times for "triggering" the sensors are about 5 to 10 minutes too early for the hall sensor and 5 minutes later for the rear bedroom sensor. In these mobile home experiments transition to flaming occurred within one hour, but the predicted results could be extended beyond this time according to Eq. (8). If the critical dose of 4.5%-min is selected, it can be shown that the two experiments did not exceed this value before flaming, but the theoretical results would achieve this critical state in about 70 minutes. In view of the degree of agreement with the data, these times are probably a reasonable estimate of hazard for the smoldering chair in the mobile home if flaming does not occur.

Another comparison of theoretical results with experiments was made for the case of a cotton mattress smoldering in a room. Two tests (JR 4 and 19) from Bukowski et al. [9] and the test (SW 13) by Hafner and Yuill [10] for a cotton mattress with a wool blanket were examined. Both rooms were the same size, but in the case of Hafner et al. two windows were open a small amount (see Table I). This was a tenuous application of the theory since the mass loss rate required was not measured for the mattresses. A gross assumption was made that the rate of heat and CO evolution was same as that measured in the NBS test for cotton (T22). The results of this comparison are shown in Figure 8. The prediction follows the data for at least the first 40 minutes but then underestimates the CO concentrations of the JR-tests and significantly overestimates the SW result. Dilution of the room gases by air flow through the windows and/or a different mass loss rate could explain the lower concentrations after 40 minutes in the SW test. Nevertheless it is surprising that the initial smoldering rate of both mattresses appears to be similar to that of the cotton material described by Eq. (8). In any case, more data from these experiments would have to have been available to draw more definite conclusions.

Since the results predicted for the smoldering chair in the mobile home are credible, the data used to describe the smoldering chair were used in a series of calculations. A room was considered with the smoldering source at 0.4 m above the floor. The height of the room was kept fixed at 2.4 m and the floor area was varied to simulate typical residential rooms up to a size representative of a single storey dwelling. Predicted CO concentrations as a function of time for various floor areas are shown in Figure 9. A hypothetical sensor at the mid-height (y=0.4) of the room was used as an indicator of hazard. The time (t_o) for the layer interface to descend to the mid-height and the critical time (t*) when a dose of 4.5%-min would be ingested are listed on the figure. It is significant to note that the critical times only vary by a factor of two for room sizes which vary by a factor of twenty. Morever, for this chair example, the layer descends to the mid-height more slowly for larger rooms, but the incremental time ($t*-t_o$) to reach the critical dose only varies from 39 to 46 minutes.

It is obvious that these calculated critical times (t*) depend on the hazard criterion adopted. The 4.5%-min dose could be considered a mild criterion. If it is increased by a factor of 4 to an 18%-min dose, although some approximations in developing Eq. (6) would be invalidated, this higher criterion is likely to correspond to a lethal condition or a serious incapacitation state [16]. The corresponding critical times would increase to 71 minutes for the 10 m^2 room and 178 minutes for the 200 m^2 room. This result for the 200 m^2 room assumes the chair continues to smolder at 73 g/min beyond its known smoldering time of two hours. Thus the higher critical dose criterion

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increases the hazard times by less than a factor of two. This probably **represents the precision** for which hazard times can be predicted since a hazard level is somewhat subjective.

From Table I a detailed view of smoldering conditions for many experimental fires has been presented. However, in that form it is difficult to draw general conclusions from those results. The mathematical model affords a means of extrapolating results from one test to other conditions, but data are lacking on mass loss rate and CO production to make these calculations. An attempt to generalize the experimental and theoretical results for predicting the CO hazard time is presented in Figure 10. The rationale for selecting the coordinates of the plot is based on the simplification that the filling process is unimportant. Then it follows from Eqns. (8) through (11) for a well-mixed space with a linearly time varying smoldering rate that

$$D = \frac{c}{6} \frac{\gamma}{\rho} \frac{t^3}{V} \tag{15}$$

where V is the volume of the enclosure. The cubic behavior in time results from the successive integration of the smoldering rate to obtain CO concentration and then dose. Thus, the critical time based on a dose of 4.5%-min. varies as the cube root of the volume and inversely as the CO production rate parameter γ. Since γ appears to not vary greatly, and a is not generally known, volume was used as the primary variable in Figure 10. Also since the smoldering rate will not increase indefinitely in time but is likely to reach a constant value then decrease as fuel is depleted, the critical time may never be achieved. Thus the volume of the space was plotted with the reciprocal of the critical time. These values were determined from Table I. Theoretical results for the chair used in the NBS experiment (see Eq. (8)) in a room of height 2.4 m

with a variable floor area are also plotted. These chair results are based on the t* values shown in Figure 9. The "JR-data" for a smoldering cotton mattress in a closed bedroom and for a bedroom open to other portions of a house tend to parallel the theoretical chair curve. This supports the credibility of the theoretical curve and suggests a family of similar curves with each corresponding to a specific smoldering rate. The range of results for the small volume spaces, indicative of single rooms, reflects the variability in the smoldering rate. Except for the NBS chair data point, the theoretical chair result represents an upper bound to the data. If this is true in general, then the curve could be considered a possible worst case. This suggests that hazardous conditions would arise as quickly as 50 to 100 minutes for typical residential rooms and dwellings.

Conclusions

An idealized mathematical model for the prediction of CO in a closed room due to a smoldering source yields results in good qualitative agreement with experimental observations and data. Good quantitative agreement appears possible provided data on the rate of smoldering and CO production are available. These data are generally lacking and therefore only a limited number of comparisons were possible. Both theory and experiment suggest that critical conditions threatening life safety (based on a 4.5%-min dose criterion) tend to arise in 50 to 100 minutes after ignition. This ignores the possibility of transition to flaming which is not a predictable event at this time.

If the results shown in Figure 1 are representative of accidental fires, then the smoldering state of a residential fire is a significant contributor to fire fatalities relative to smoldering fires which go to a flaming state, provided

the 4.5%-min dose criterion is accepted as a serious hazard level. If one uses the 18%-min criterion, then at least ten percent of the available experimental fires reached this level in the smoldering state. The conditions arising after transition to flaming would be responsible for the remainder of the fatalities, and more than half of the experimental fires reviewed eventually resulted in flaming combustion.

The single-space model suggests that the volume of the space is not a strong influencing factor on the time to reach a hazardous condition (i.e., critical dose time). Data [9] show a two-fold increase in critical time for a ten-fold increase in volume. More complete experiments of smoldering in a residential dwelling need to be examined to determine whether a more sophis-ticated theoretical model is needed to make predictions. Also the phenomena of smoldering "smoke" movement in a multi-room space needs to be clearly established. As these gases cool they will not be driven by the buoyancy produced from combustion but will follow the natural and forced ventilation characteristics of the building.

If materials were characterized by their rate of smoldering ($\dot{m}(t)$) and their CO production (γ), the simple model developed here could provide a means of assessing risk. Characteristic mass loss (or CO production) rates need to be measured for smolderable materials in their product configuration. Such a study would quantitatively define the fire problem of smoldering. The use of "small-scale" tests to measure γ values appears feasible, but the constancy of γ and its variation among materials or configurations needs to be explored.

Acknowledgement

The authors wish to acknowledge the work of Ken Steckler who developed the computer program for solving the equations used in the model, and to Maya Paabo who supplied specie data on the decomposition products of the cotton and polyurethane materials used in the NBS experiments.

<center>Nomenclature</center>

a,b,c	fixed parameters,
D	dose, Eq. (4)
c_p	specific heat
g	ravitational acceleration
H	vertical distance from source to hot layer
H_c	vertical distance from source to ceiling
L	vertical distance from source to floor
m	mass loss
$\dot{m}$	mass loss rate
$\dot{Q}$	rate of energy release
Q*	dimensionless heat source, $\dot{Q}/(\rho_o T_o c_p \sqrt{gH_c}\ H_c^2)$
S	floor area
t	time
t*	critical time at D = 4.5 %-min
T	Temperature
V	volume of room
x	volume concentration of CO in percent
y	dimensionless distance, H/H_c
Y	mass concentration of CO
z	percent saturation of COHb in blood
α	entrainment constant, 1/5.4
γ	mass ratio of CO produced to mass loss in smoldering
ΔH	effective heat of reaction
ρ	density of gas
τ	dimensionless time, $t\sqrt{g/H_c}\ (H_c^2/S)$

Subscripts

CO   carbon monoxide

f   final state

o   initial state

O_2 oxygen

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Figure 1. Distribution of smoldering experiments in Table I for occurrence of critical CO dose and transition to flaming
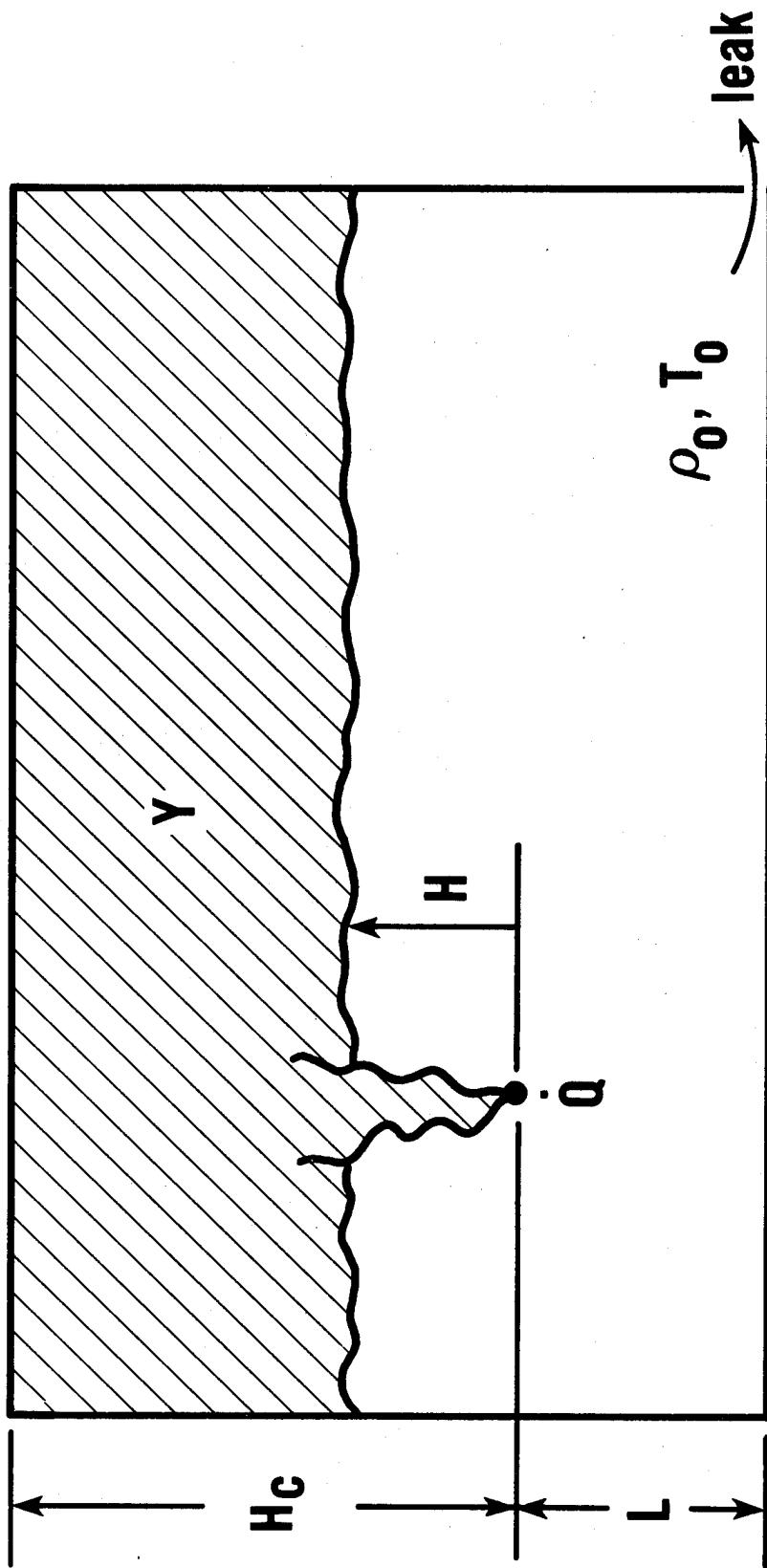
Figure 2. Idealization mathematical modeling for smoldering in a nearly closed compartment
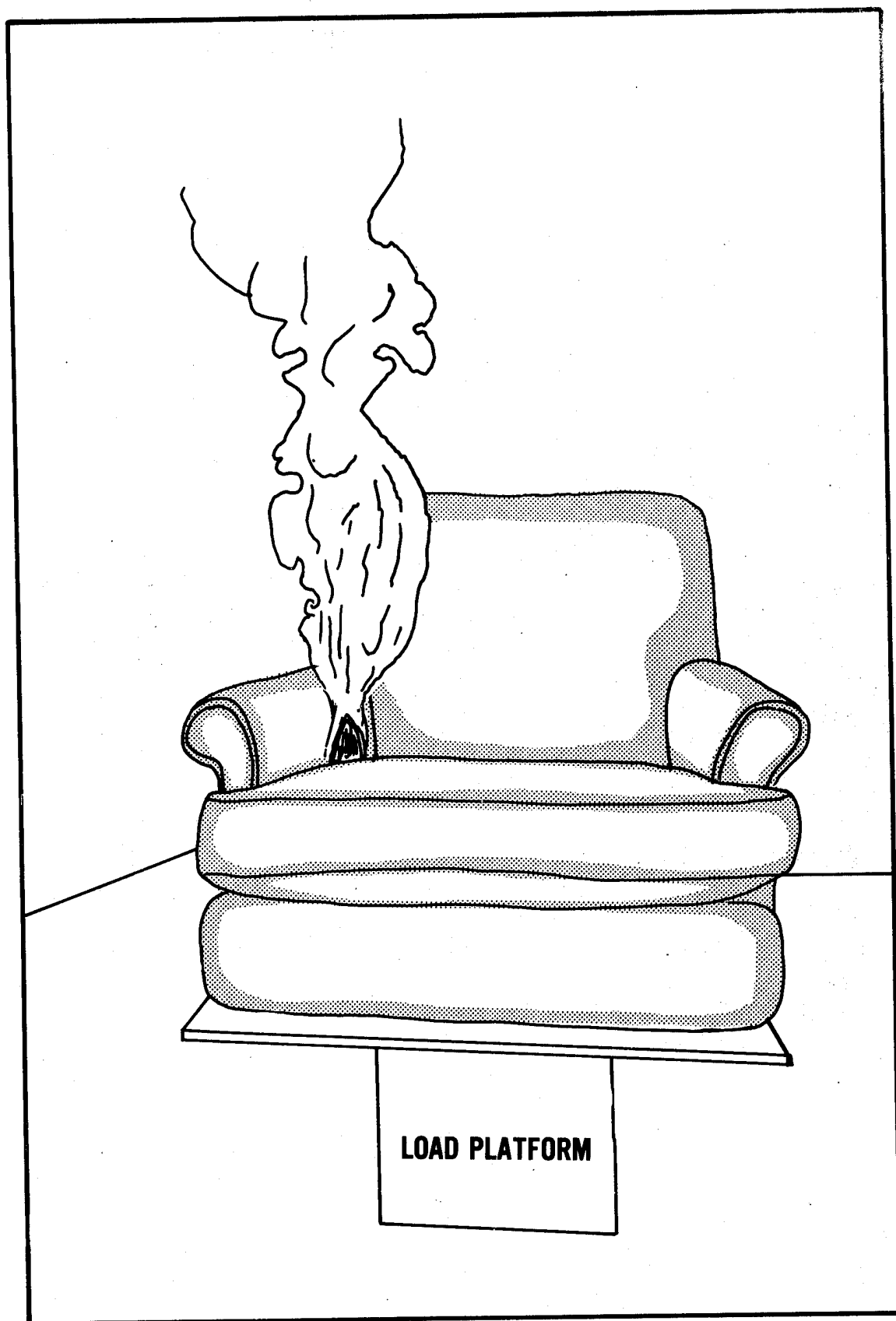
Figure 3. Sketch from a photograph of a smoldering smoke plume
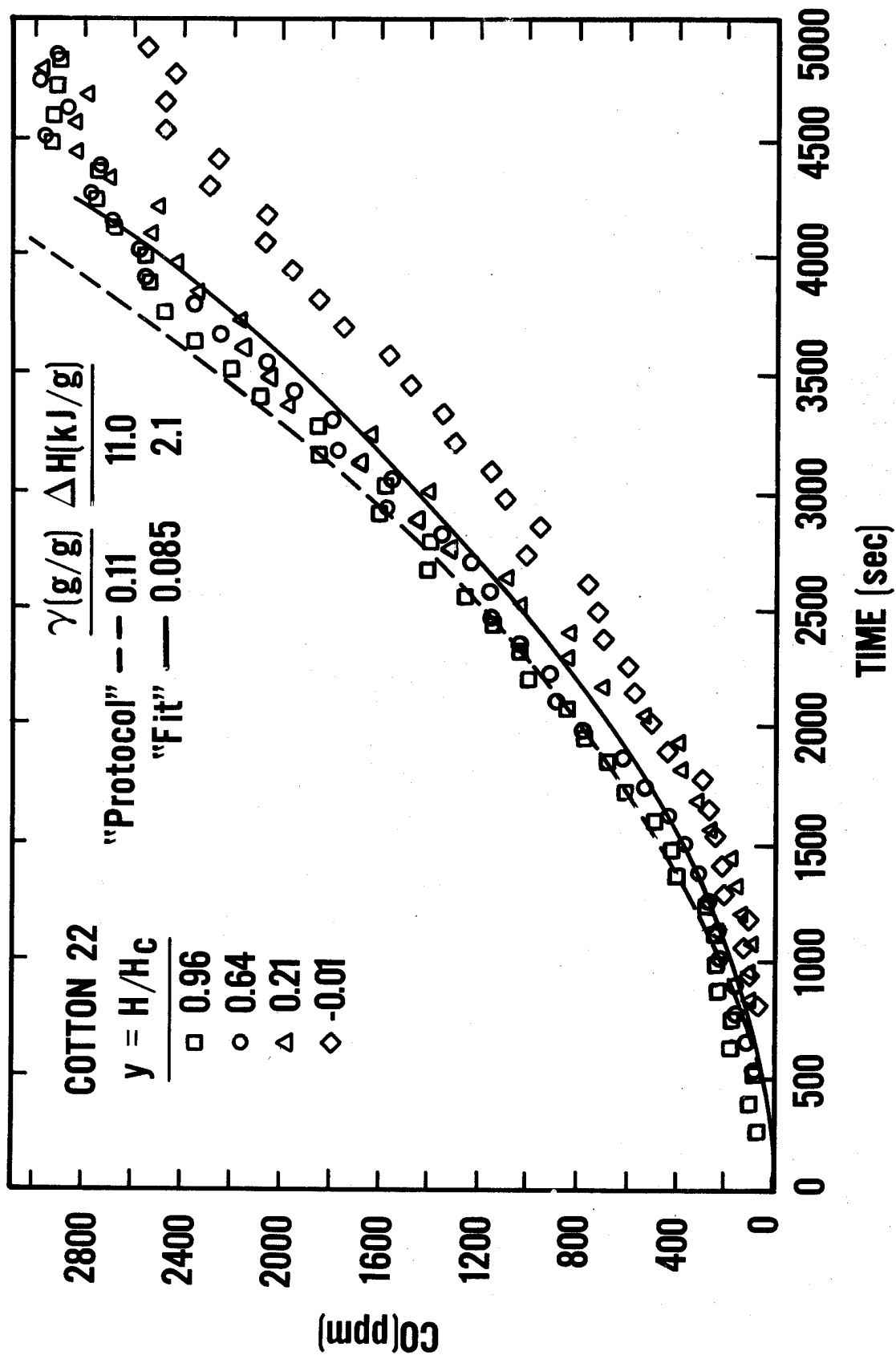
Figure 4.   Calculated and measured CO concentrations for loosely packed bed of cotton
smoldering in a closed room
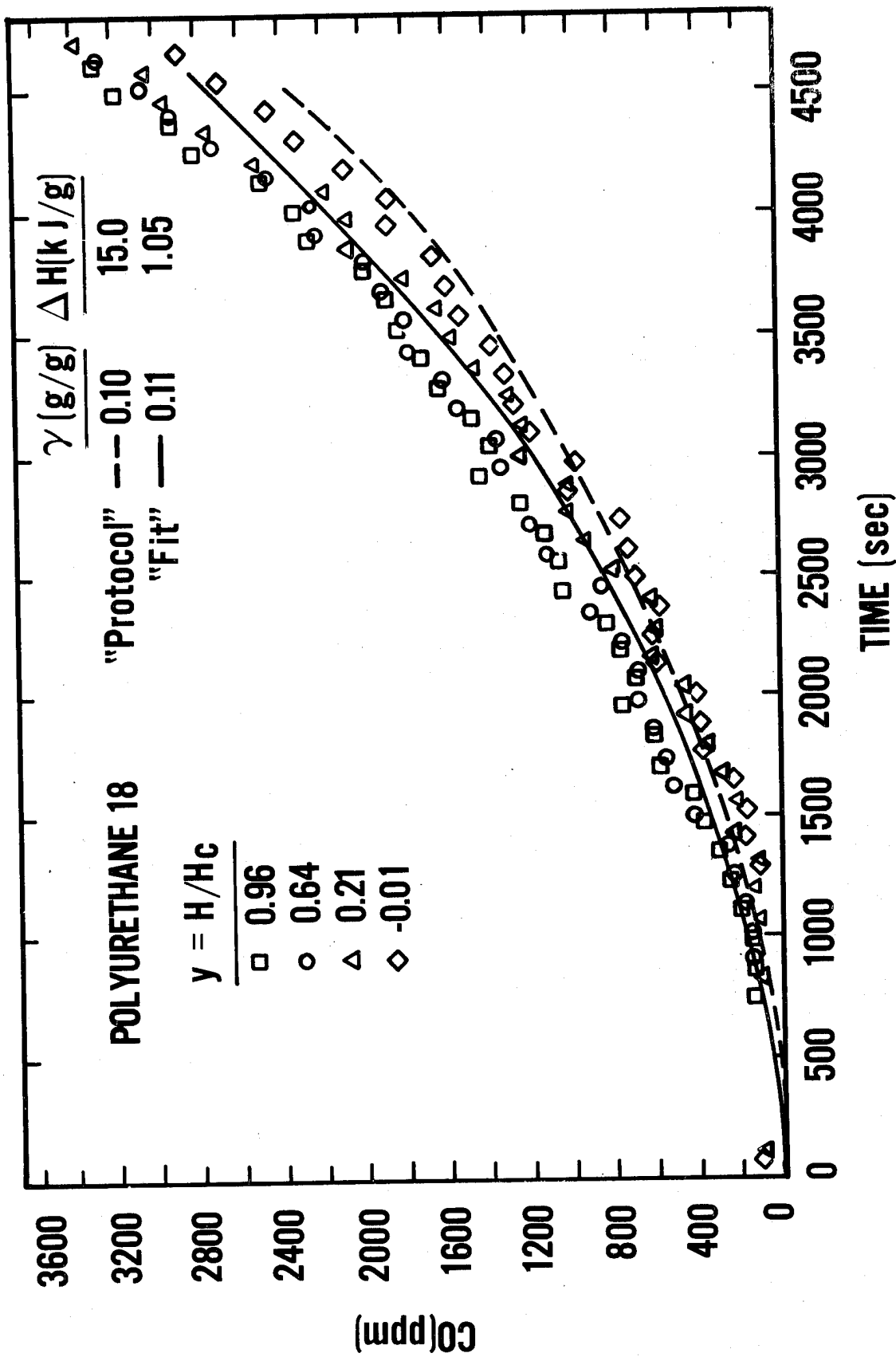
Figure 5. Calculated and measured CO concentrations for a block of flexible polyurethane foam smoldering in a closed room

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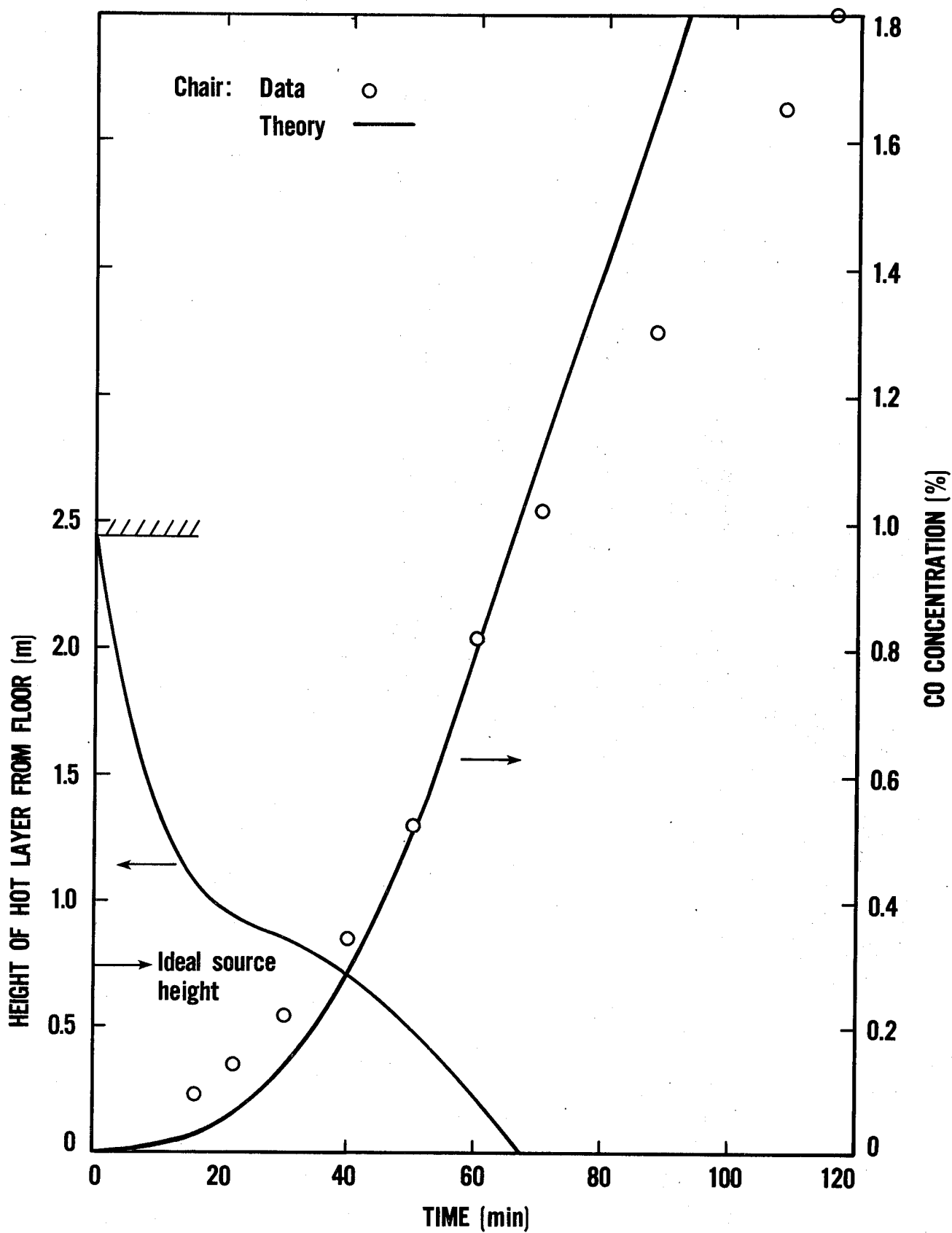
Figure 6. Calculated and measured results for a chair smoldering in a closed room
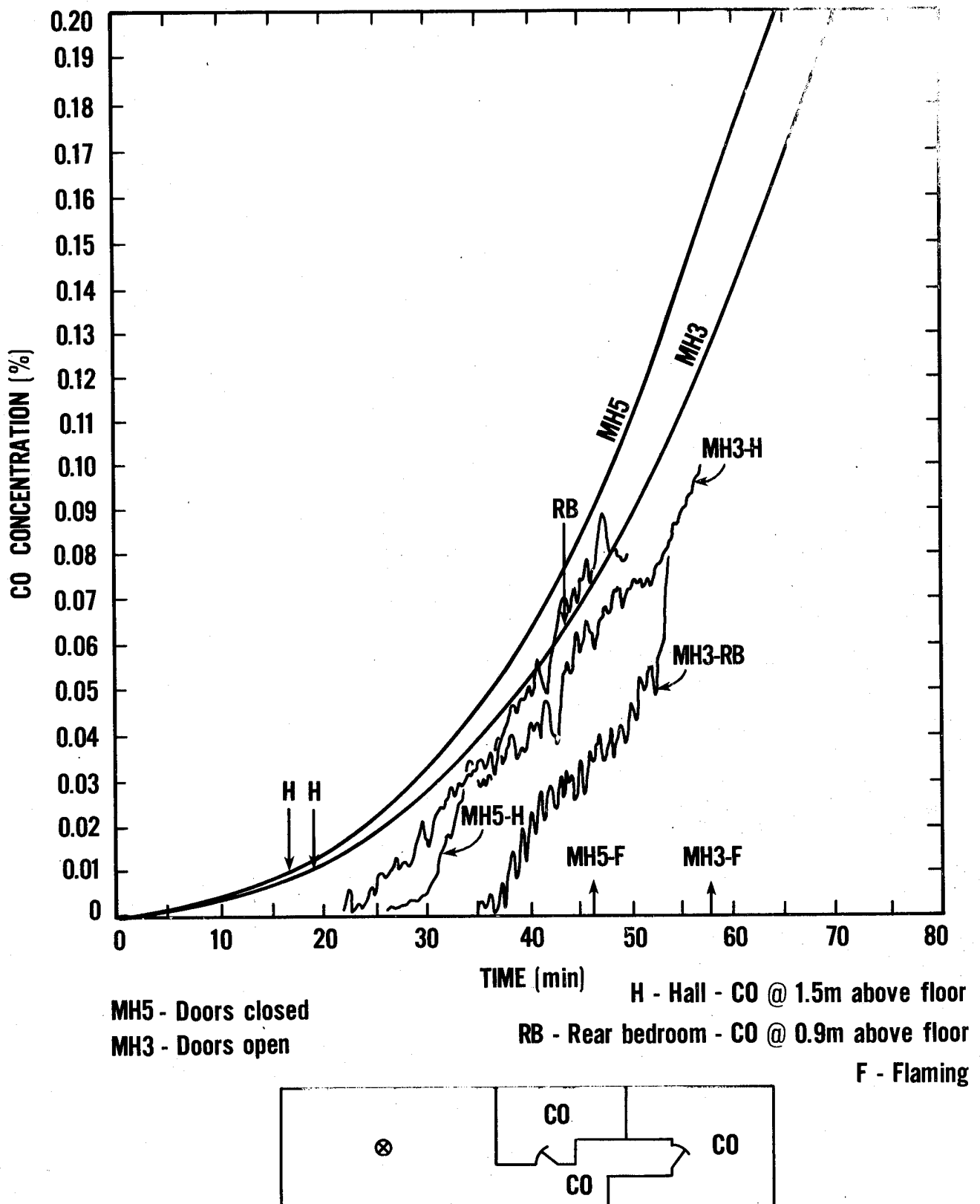
Figure 7. Calculated and measured CO concentrations for a chair smoldering in a closed mobile home. ⊗ Chair location
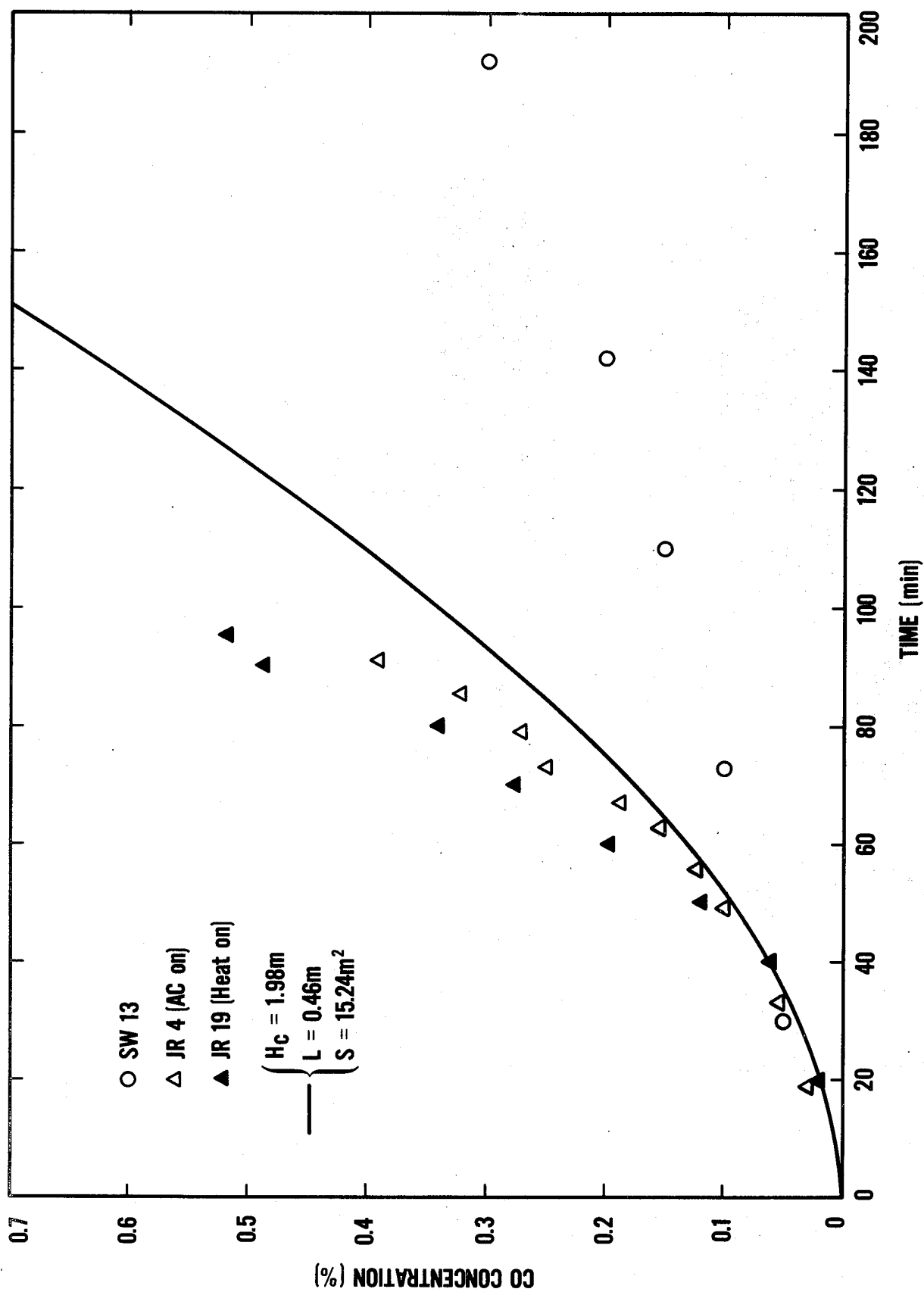
Figure 8. Measured results for cotton mattresses smoldering in a room compared with calculated values based on the smoldering of loosely packed cotton

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S=10m² 16m² 25m²

50m²

S = floor area

$y = H/H_C$

$H_C = 2.0m$

$L = 0.4m$

0.40

0.35

0.30

0.25

0.20

0.15

0.10

0.05

0

CO CONCENTRATION [%]

S(m²)	t_0(min)	t^*(min)
10	9	48
16	12	53
25	17	60
50	26	72
100	40	86
200	61	107

100m²

200m²

Critical dose: $\int_{t_0}^{t^*} Y_{CO}\,dt = 4.5\%\text{-min}$

$y(t_0) = 0.4$

0   20   40   60   80   100   120

TIME (min)

Figure 9.   Theoretical results for a chair smoldering in rooms of various volume

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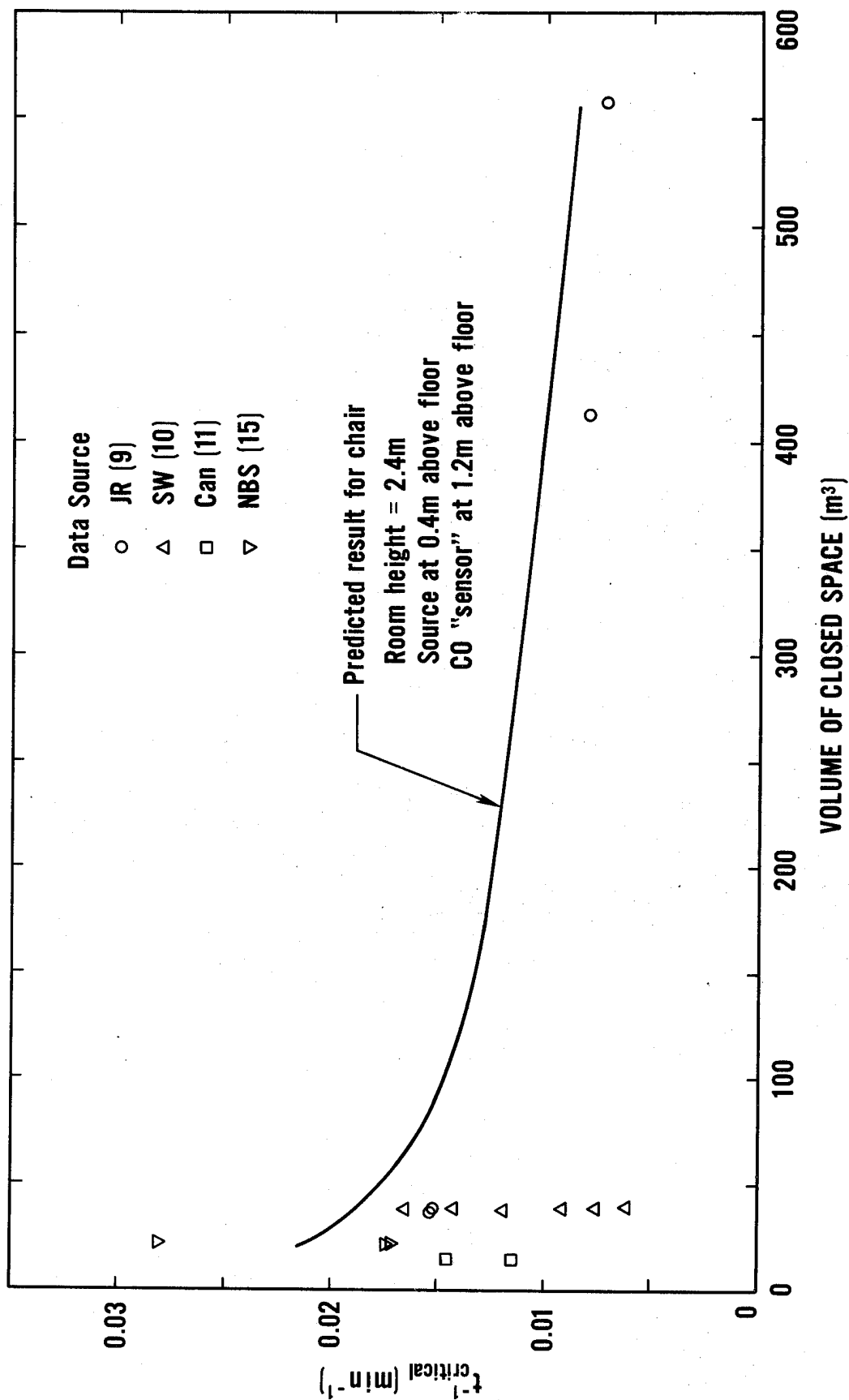
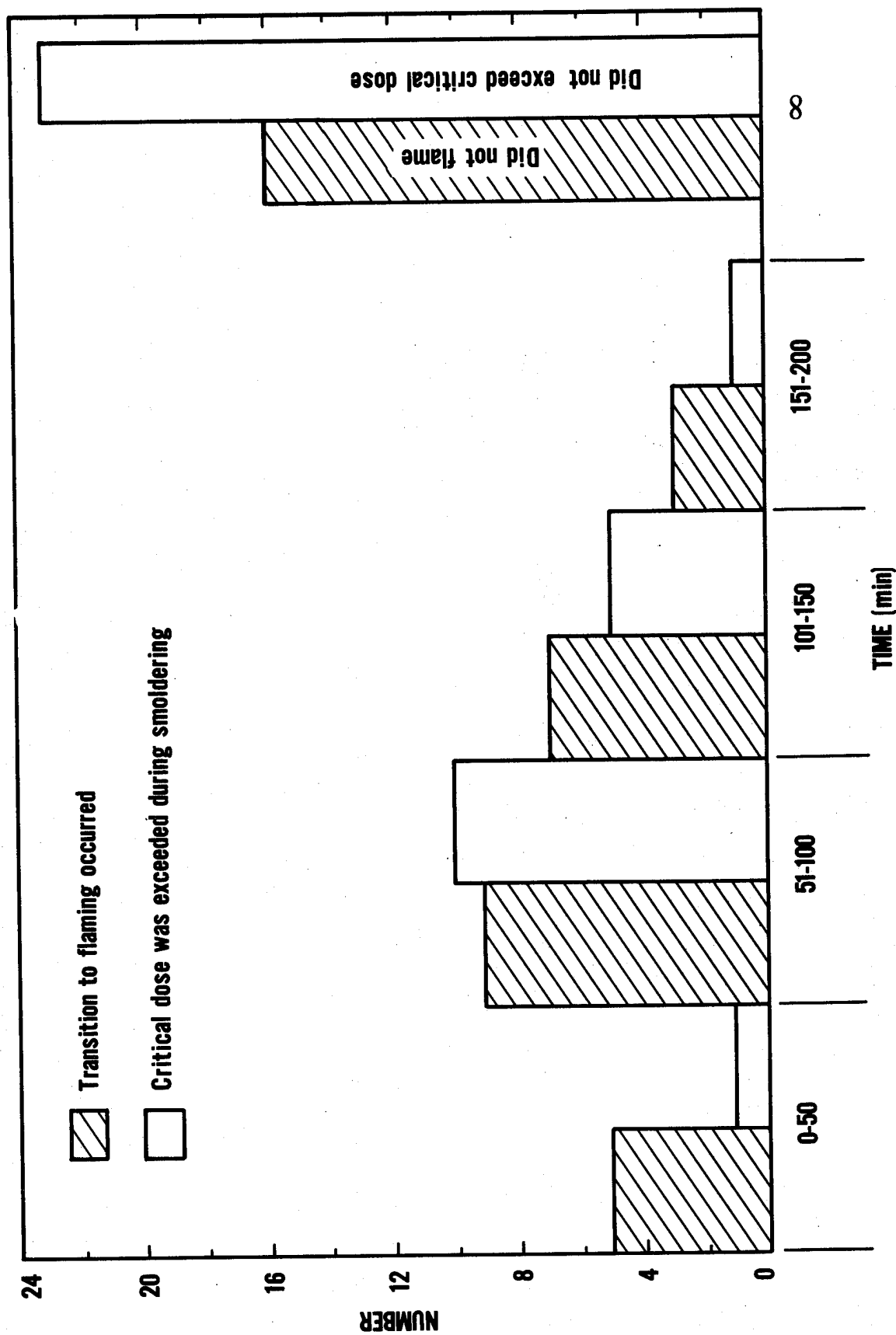Figure 10. A correlation of CO critical time with room volume from Table I and theory

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SUMMARY OF EXPERIMENTAL RESULTS FOR SMOLDERING IN A NEARLY CLOSED SPACE

TABLE IA

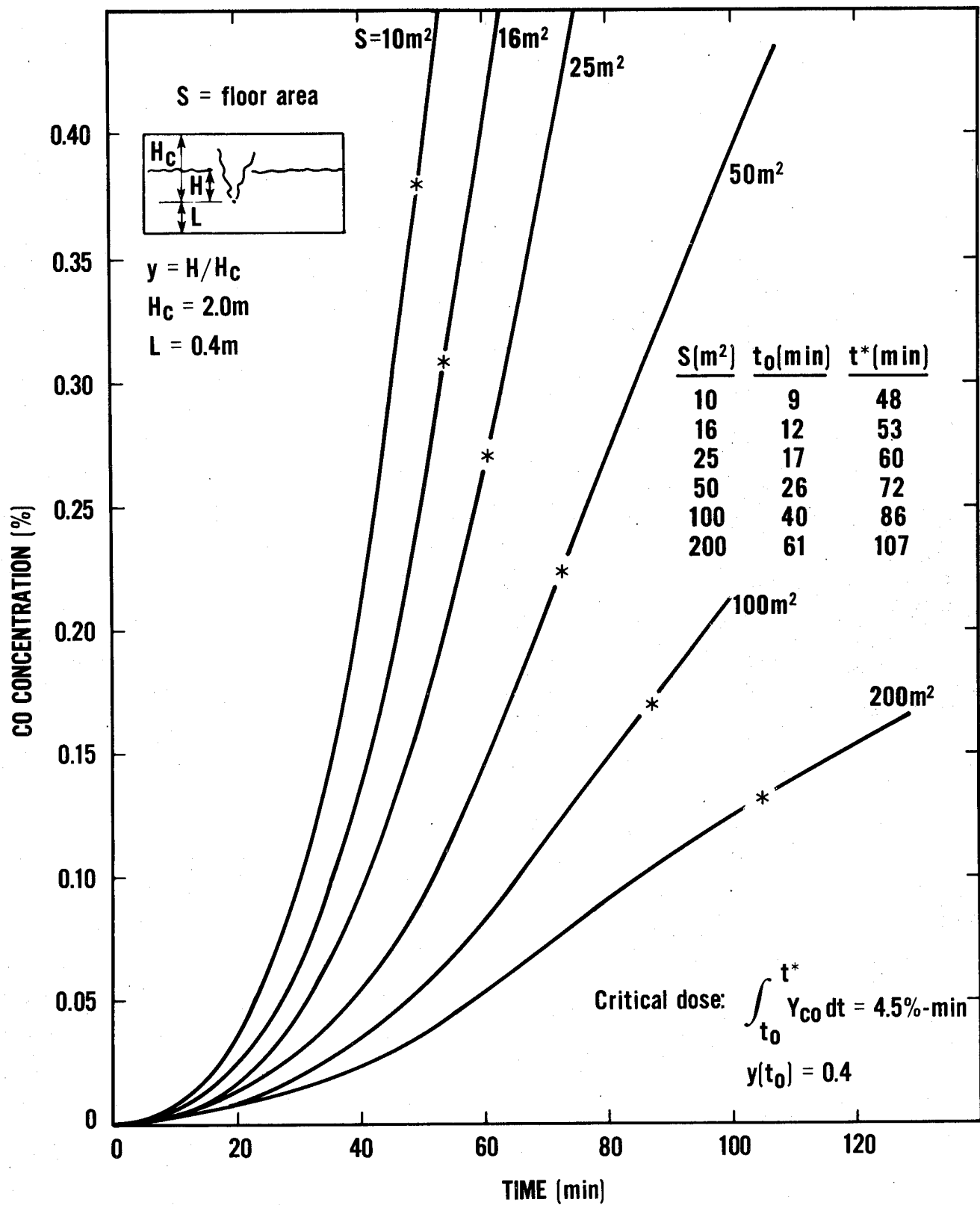| Test Number	Reference	Material	Type of Enclosure* (closed space)	Volume of Enclosure m³	Ventilation Condition
JR4	9	Cot. mattress	Bedroom (BR)	37.0	A.C.
JR5	9	Cot. mattress	BR, hall, LR	247.1	A.C.
JR6	9	Cot. mattress	BR, 1st & 2nd flr.	370.7	A.C.
JR10	9	Cot. mattress	Bsmt, 1st flr. hall & LR, 2nd flr.	413.2	A.C.
JR12	9	Cot. mattress	Bsmt, 1st & 2nd flr.	566.0	A.C.
JR11	9	Cot. box spring	Bsmt, 1st flr. LR & hall, 2nd flr. hall	413.2	A.C.
JR14	9	Chair: cot., ray., acetate	LR, 1st & 2nd flr. halls, two BR's	325.5	Heat
JR15	9	Chair: cot., ray.	LR, 1st & 2nd flr. halls, BR	325.5	None
JR17	9	Cot. mattress	BR, 1st & 2nd flr.	370.7	Heat
JR18	9	Cot. mattress	BR, LR, 1st & 2nd flr. halls	247.1	None
JR19	9	Cot. mattress	BR	37.0	Heat
JR22	9	Chair: cot., ray.	Bsmt, 1st & 2nd flr.	566.0	Heat
JR24	9	Sofa: cot., ny.	Bsmt. 1st & 2nd flr.	566.0	None
JR26	9	Couch: cot., ray., ny.	Bsmt, portions of 1st & 2nd flr.	501.0	Heat
SW1	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets	Room	38.0	two windows 5cm x 91cm
SW4	10	Cot. inner-spring mattress, ray. tick; cot. percale sheets	Room	38.0	" " " "
SW5	10	Cot. inner-spring mattress, ray. tick; cot. sheets	Room	38.0	" " " "
SW6	10	Cot. inner-spring mattress, cot. tick; cot. muslin sheets	Room	38.0	" " " "
SW9	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; ray., acry. blanket	Room	38.0	" " " "
SW10	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; cot. blanket	Room	38.0	" " " "
SW11	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; polyester blanket	Room	38.0	" " " "
SW13	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; wool blanket	Room	38.0	" " " "
SW18	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; acrylic blanket (laundered)	Room	38.0	" " " "
SW19	10	Cot. inner-spring mattress, tick; cot. muslin sheet; wool blanket (retarded)	Room	38.0	" " " "

Test Number	Reference	Material	Type of Enclosure* (closed space)	Volume of Enclosure m³	Ventilation Condition	
SW21	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheet & feather pillow	Room	38.0	"	"
					"	"
SW23	10	Chair/cushion: polyu./fabric: ny.	Room	38.0	"	"
					"	"
SW25	10	Chair/cushion: rubber/fabric: ny.	Room	38.0	"	"
					"	"
SW24	10	Chair/cushion: polyu./ fabric: cot.	Room	38.0	"	"
					"	"
SW26	10	Chair/cushion: polyu./fabric: ny.	Room	38.0	"	"
					"	"
SW27	10	Chair/cushion: polyu./fabric: acetate	Room	38.0	"	"
					"	"
SW28	10	Chair/cushion: polyu./fabric: polypropylene	Room	38.0	"	"
					"	"
Can2	11	Cot. inner-spring mattress, 1/2	Room	14.5	None	
Can3	11	Cot. inner-spring mattress, 1/2	Room	14.5	" "	
MH03	12	Chair: cot., polyu.	Mobile home: LR., Kit., hall, BR.	134.4	" "	
MH05	12	Chair: cot., polyu.	Mobile home: LR., Kit., hall	99.1	" "	
FM1	13	Sofa cushion: polyu.	Apartment	170.	Heat	
FM2	13	Sofa cushion: polyu.	Apartment	170.	" "	
T18	15	Polyu. (two blocks, 15cm thk.)	Room	21.5	" "	
T22	15	Cot. (10-15 cm thk.)	Room	21.5	None	
-	15	Chair: cot., polyu.	Room	21.5	None	

*First room listed contains smoldering material; underlined room is measurement location
Note Abbreviations:

A.C.	-	air conditioning
BR	-	bedroom
LR	-	living room
Bsmt.	-	basement
kit.	-	kitchen
cot.	-	cotton
ray.	-	rayon
ny.	-	nylon
acry.	-	acrylic
polyes.	-	polyester
polyu.	-	polyurethane

Test No.	Max. CO %	Time Min.	Min. O_2 %	Time Min.	Max. CO_2 %	Time Min.	Max. ΔT °C	Time Min.	Max $\int_0^t [CO]dt$ % - min	Time Min.	Critical Dose Time Min.	Flaming Time Min.
JR4	0.39	93.	–	–	1.32	92.	27.	93.	11.0	93.	65.	94.5
JR5	0.20	51.	–	–	0.8	51.	29.	51.	2.2	51.	∞	51.
JR6	0.095	73.	–	–	0.45	73.	15.	73.	2.9	73.	∞	∞
JR10	0.23	137.	–	–	1.25	137.	5.	118.	7.0	140.	125.	∞
JR12	0.16	140.	–	–	1.05	140.	14.	140.	4.5	140.	140.	∞
JR11	0.11	130.	–	–	0.33	130.	11.	130.	4.0	130.	∞	130.
JR14	0.02	100.	–	–	0.1	100.	13.	100.	< 1.0	100.	∞	∞
JR15	0.03	80.	–	–	0.06	80.	0.	80.	< 1.0	80.	∞	∞
JR17	0.10	70.	–	–	0.55	70.	11.	70.	2.3	70.	∞	∞
JR18	0.08	63.	–	–	0.34	63.	9.	63.	2.2	63.	∞	∞
JR19	0.55	100.	–	–	2.5	100.	24.	100.	18.0	100.	65.	∞
JR22	∼ 0	27.	–	–	∼ 0	27.	0.	27.	< 1.0	27.	∞	27.
JR24	0.01	107.	–	–	0.11	107.	-2.	107.	< 1.0	107.	∞	107.
JR26	0.02	84.	–	–	0.15	84.	3.	85.	< 1.0	86.	∞	86.
SW1	0.2	121.	20.5	121.	0.5	121.	22.	121.	3.9	121.	∞	121.
SW4	0.4	135.	18.	135.	0.3	135.	45.	155.	29.4	200.	110.	∞
SW5	0.2	162.	20.	160.	1.0	160.	15.	160.	8.6	160.	130.	162.
SW6	0.15	118.	18.5	118.	1.5	118.	60.	118.	4.0	118.	∞	118.
SW9	0.1	91.	20.	91.	0.5	91.	8.	91.	4.3	91.	∞	97.
SW10	0.15	100.	20.	100.	1.0	100.	0.	100.	6.5	100.	85.	100.
SW11	0.15	175.	20.	175.	2.0	175.	15.	175.	5.3	175.	165.	175.
SW13	0.39	220.	18.4	220.	2.8	220.	61.	220.	36.5	220.	70.	∞
SW18	0.1	114.	20.	114.	1.0	114.	3.	114.	4.8	114.	110.	114.
SW19	0.05	190.	20.5	190.	0.5	190.	0.	190.	< 1.0	190.	∞	∞
SW21	0.22	180.	20.2	180.	1.2	180.	21.	180.	13.0	180.	60	∞
SW23	0.05	144.	20.	144.	1.0	144.	17.	144.	3.8	144.	∞	144.
SW25	0.1	65.	20.	65.	1.0	65.	6.	65.	2.5	65.	∞	65.
SW24	0.07	77.	20.4	77.	0.8	77.	0.	77.	2.7	77.	∞	77.
SW26	0.05	152.	20.	152.	1.	152.	4.	152.	2.3	152.	∞	152.
SW27	0.15	124.	17.	124.	1.0	124.	11.	124.	6.3	124.	90.	124.
SW28	0.1	22.	20.8	22.	0.02	22.	0.	22.	1.1	22.	∞	22.
Can 2	0.3	117.	17.6	120.	3.0	120.	24.	118.	11.1	117.	87.	∞
Can 3	0.5	108.	16.0	100.	4.8	103.	35.	105.	17.3	108.	69.	∞
MH03	0.10	57.	–	–	0.2	57.	2.	57.	2.2	57.	∞	57.
MH05	0.08	46.	–	–	0.2	46.	2.	46.	1.0	46.	∞	46.
FM1	0.013	38.	21.	38.	0.	38.	2.	38.	< 1.0	39.	∞	39.
FM2	0.011	40.	21.	40.	0.04	40.	3.	40.	< 1.0	41.	∞	41
T18	0.34	79.	–	–	0.47	79.	13.	79.	11.5	79.	58.	98.
T22	0.3	92.	–	–	1.6	92.	12.	75.	11.7	83.	60.	∞
–	1.8	116.	–	–	–	–	–	–	90.	116.	36.	∞

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TABLE IA

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JR11	9	Cot. box spring	Bsmt, 1st flr. LR & hall, 2nd flr. hall	413.2	A.C.
JR14	9	Chair: cot., ray., acetate	LR, 1st & 2nd flr. halls, two BR's	325.5	Heat
JR15	9	Chair: cot., ray.	LR, 1st & 2nd flr. halls, BR	325.5	None
JR17	9	Cot. mattress	BR, 1st & 2nd flr.	370.7	Heat
JR18	9	Cot. mattress	BR, LR, 1st & 2nd flr. halls	247.1	None
JR19	9	Cot. mattress	BR	37.0	Heat
JR22	9	Chair: cot., ray.	Bsmt, 1st & 2nd flr.	566.0	Heat
JR24	9	Sofa: cot., ny.	Bsmt. 1st & 2nd flr.	566.0	None
JR26	9	Couch: cot., ray., ny.	Bsmt, portions of 1st & 2nd flr.	501.0	Heat
SW1	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets	Room	38.0	two windows 5cm x 91cm
SW4	10	Cot. inner-spring mattress, ray. tick; cot. percale sheets	Room	38.0	" " " "
SW5	10	Cot. inner-spring mattress, ray. tick; cot. sheets	Room	38.0	" " " "
SW6	10	Cot. inner-spring mattress, cot. tick; cot. muslin sheets	Room	38.0	" " " "
SW9	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; ray., acry. blanket	Room	38.0	" " " "
SW10	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; cot. blanket	Room	38.0	" " " "
SW11	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; polyester blanket	Room	38.0	" " " "
SW13	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; wool blanket	Room	38.0	" " " "
SW18	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheets; acrylic blanket (laundered)	Room	38.0	" " " "
SW19	10	Cot. inner-spring mattress, tick; cot. muslin sheet; wool blanket (retarded)	Room	38.0	" " " "

Test Number	Reference	Material	Type of Enclosure* (closed space)	Volume of Enclosure m^3	Ventilation Condition	
SW21	10	Cot. inner-spring mattress, ray. tick; cot. muslin sheet & feather pillow	Room	38.0	" "	" "
SW23	10	Chair/cushion: polyu./fabric: ny.	Room	38.0	" "	" "
SW25	10	Chair/cushion: rubber/fabric: ny.	Room	38.0	" "	" "
SW24	10	Chair/cushion: polyu./ fabric: cot.	Room	38.0	" "	" "
SW26	10	Chair/cushion: polyu./fabric: ny.	Room	38.0	" "	" "
SW27	10	Chair/cushion: polyu./fabric: acetate	Room	38.0	" "	" "
SW28	10	Chair/cushion: polyu./fabric: polypro-pylene	Room	38.0	" "	" "
Can2	11	Cot. inner-spring mattress, 1/2	Room	14.5	None	
Can3	11	Cot. inner-spring mattress, 1/2	Room	14.5	" "	
MH03	12	Chair: cot., polyu.	Mobile home: LR., Kit., hall, BR.	134.4	" "	
MH05	12	Chair: cot., polyu.	Mobile home: LR., Kit., hall	99.1	" "	
FM1	13	Sofa cushion: polyu.	Apartment	170.	Heat	
FM2	13	Sofa cushion: polyu.	Apartment	170.	" "	
T18	15	Polyu. (two blocks, 15cm thk.)	Room	21.5	" "	
T22	15	Cot. (10-15 cm thk.)	Room	21.5	None	
—	15	Chair: cot., polyu.	Room	21.5	None	

*First room listed contains smoldering material; underlined room is measurement location
Note Abbreviations:

A.C.	–	air conditioning
BR	–	bedroom
LR	–	living room
Bsmt.	–	basement
kit.	–	kitchen
cot.	–	cotton
ray.	–	rayon
ny.	–	nylon
acry.	–	acrylic
polyes.	–	polyester
polyu.	–	polyurethane

SUMMARY OF EXPERIMENTAL RESULTS FOR SMOLDERING IN A NEARLY CLOSED SPACE
TABLE Ib

Test No.	Max. CO %	Time Min.	Min. O_2 %	Time Min.	Max. CO_2 %	Time Min.	Max. ΔT °C	Time Min.	Max $\int_o^t$ [CO]dt % – min	Time Min.	Critical Dose Time Min.	Flaming Time Min.
JR4	0.39	93.	–	–	1.32	92.	27.	93.	11.0	93.	65.	94.5
JR5	0.20	51.	–	–	0.8	51.	29.	51.	2.2	51.	∞	51.
JR6	0.095	73.	–	–	0.45	73.	15.	73.	2.9	73.	∞	∞
JR10	0.23	137.	–	–	1.25	137.	5.	118.	7.0	140.	125.	∞
JR12	0.16	140.	–	–	1.05	140.	14.	140.	4.5	140.	140.	∞
JR11	0.11	130.	–	–	0.33	130.	11.	130.	4.0	130.	∞	130.
JR14	0.02	100.	–	–	0.1	100.	13.	100.	< 1.0	100.	∞	∞
JR15	0.03	80.	–	–	0.06	80.	0.	80.	< 1.0	80.	∞	∞
JR17	0.10	70.	–	–	0.55	70.	11.	70.	2.3	70.	∞	∞
JR18	0.08	63.	–	–	0.34	63.	9.	63.	2.2	63.	∞	∞
JR19	0.55	100.	–	–	2.5	100.	24.	100.	18.0	100.	65.	∞
JR22	∿ 0	27.	–	–	∿ 0	27.	0.	27.	< 1.0	27.	∞	27.
JR24	0.01	107.	–	–	0.11	107.	-2.	107.	< 1.0	107.	∞	107.
JR26	0.02	84.	–	–	0.15	84.	3.	85.	< 1.0	86.	∞	86.
SW1	0.2	121.	20.5	121.	0.5	121.	22.	121.	3.9	121.	∞	121.
SW4	0.4	135.	18.	135.	0.3	135.	45.	155.	29.4	200.	110.	∞
SW5	0.2	162.	20.	160.	1.0	160.	15.	160.	8.6	160.	130.	162.
SW6	0.15	118.	18.5	118.	1.5	118.	60.	118.	4.0	118.	∞	118.
SW9	0.1	91.	20.	91.	0.5	91.	8.	91.	4.3	91.	∞	97.
SW10	0.15	100.	20.	100.	1.0	100.	0.	100.	6.5	100.	85.	100.
SW11	0.15	175.	20.	175.	2.0	175.	15.	175.	5.3	175.	165.	175.
SW13	0.39	220.	18.4	220.	2.8	220.	61.	220.	36.5	220.	70.	∞
SW18	0.1	114.	20.	114.	1.0	114.	3.	114.	4.8	114.	110.	114.
SW19	0.05	190.	20.5	190.	0.5	190.	0.	190.	< 1.0	190.	∞	∞
SW21	0.22	180.	20.2	180.	1.2	180.	21.	180.	13.0	180.	60	∞
SW23	0.05	144.	20.	144.	1.0	144.	17.	144.	3.8	144.	∞	144.
SW25	0.1	65.	20.	65.	1.0	65.	6.	65.	2.5	65.	∞	65.
SW24	0.07	77.	20.4	77.	0.8	77.	0.	77.	2.7	77.	∞	77.
SW26	0.05	152.	20.	152.	1.	152.	4.	152.	2.3	152.	∞	152.
SW27	0.15	124.	17.	124.	1.0	124.	11.	124.	6.3	124.	90.	124.
SW28	0.1	22.	20.8	22.	0.02	22.	0.	22.	1.1	22.	∞	22.
Can 2	0.3	117.	17.6	120.	3.0	120.	24.	118.	11.1	117.	87.	∞
Can 3	0.5	108.	16.0	100.	4.8	103.	35.	105.	17.3	108.	69.	∞
MH03	0.10	57.	–	–	0.2	57.	2.	57.	2.2	57.	∞	57.
MH05	0.08	46.	–	–	0.2	46.	2.	46.	1.0	46.	∞	46.
FM1	0.013	38.	21.	38.	0.	38.	2.	38.	< 1.0	39.	∞	39.
FM2	0.011	40.	21.	40.	0.04	40.	3.	40.	< 1.0	41.	∞	41
T18	0.34	79.	–	–	0.47	79.	13.	79.	11.5	79.	58.	98.
T22	0.3	92.	–	–	1.6	92.	12.	75.	11.7	83.	60.	∞
–	1.8	116.	–	–	–	–	–	–	90.	116.	36.	∞

4. TITLE AND SUBTITLE

An Analysis of Smoldering Fires in Closed Compartments and Their Hazard Due to Carbon Monoxide

5. AUTHOR(S)

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6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)* A review was made of smoldering fire experiments conducted in closed room and buildings. The results were summarized by tabulating maximum levels of CO, the time integral of CO concentration ("dose"), CO_2, temperature rise and oxygen consumption. A hazard time based on the attainment of a CO dose equal to 4.5% CO-minutes and the time for transition to flaming were also tabulated. The likelihood of reaching a critical CO condition during smoldering seems to be comparable to the likelihood of having transition to flaming occur. A theoretical model, requiring inputs of CO production rate and energy release rate, was executed and compared with available data. The theoretical results for CO concentration as a function of time were in good agreement with the experimental data. The model offers a means of extrapolating test data to compartments of various size in order to assess the general hazard of CO due to smoldering.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Building fires; carbon monoxide; compartment fires; smoldering